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14. ABSTRACT
Experiments with ultrasonically-excited viscous test liquid have occurred at various conditions over several months. These tests were intended to examine the qualitative response of the liquid and the cavitation effects to assorted variables, including pressure, dissolved gas content, suspended gas bubble content, and the physical parameters of the test cell cavity. Tests were conducted using the test liquid and various means of securing the separation membrane onto the test cavity (between the test liquid and the ultrasonically conductive medium). Both water and gel were tested as potential media for conducting ultrasonic energy into the test cavity. Separation membranes of 0.001" and 0.005" have been tested. Tests have been performed with the liquid hand-poured into the test cavity, or drawn in via vacuum from an external pressurized tank, likely influencing the amount of dissolved gas. Micron-scale gas bubbles (argon, air) were purposely suspended in the viscous test liquid prior to some tests. Tests were run using liquid pressures ranging from ambient up to 450 psi. Ultrasonic powers from 1-200 Watts net (forward minus reflected powers) were used to excite the test liquid (though some dissipation likely occurred prior to the test cavity).

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Informal Summary of Ultrasonic Excitation of Viscous Test Liquid

-David Scharfe-

Overall Test Summary:

Experiments with ultrasonically-excited viscous test liquid have occurred at various conditions over several months. These tests were intended to examine the qualitative response of the liquid and the cavitation effects to assorted variables, including pressure, dissolved gas content, suspended gas bubble content, and the physical parameters of the test cell cavity. Tests were conducted using the test liquid and various means of securing the separation membrane onto the test cavity (between the test liquid and the ultrasonically conductive medium). Both water and gel were tested as potential media for conducting ultrasonic energy into the test cavity. Separation membranes of 0.001" and 0.005" have been tested. Tests have been performed with the liquid hand-poured into the test cavity, or drawn in via vacuum from an external pressurized tank, likely influencing the amount of dissolved gas. Micron-scale gas bubbles (argon, air) were purposely suspended in the viscous test liquid prior to some tests. Tests were run using liquid pressures ranging from ambient up to 450 psi. Ultrasonic powers from 1-200 Watts net (forward minus reflected powers) were used to excite the test liquid (though some dissipation likely occurred prior to the test cavity).

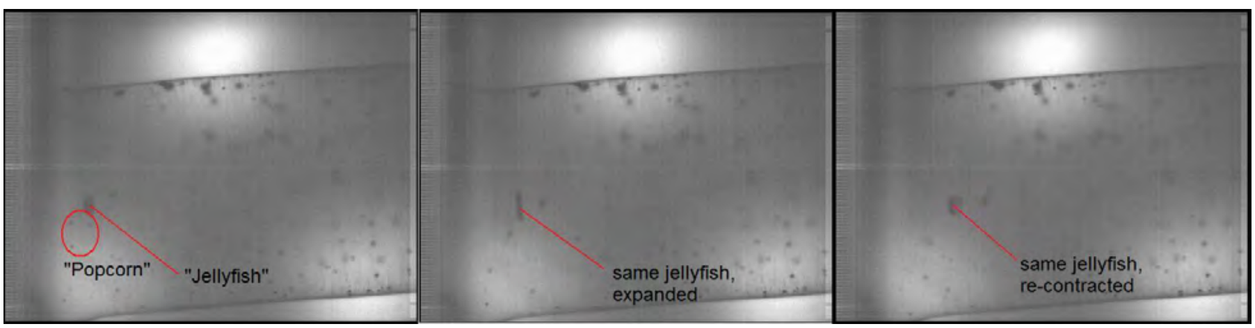
Overall, the iterative testing revealed that cavitation effects were most readily observed using a hand-poured test liquid (likely extra dissolved gas, as well as trapped gas pockets in the test cavity), the ultrasonically conductive gel (as opposed to water), and a 0.001" membrane. For the various high pressure tests described below, the test liquid was drawn into an evacuated cavity, and then pressure was applied to the external tank. Valves were then closed and the pressure outside the test cavity was relieved. For the 50, 200, and 400 psi cases, the same liquid was used without breaking the test cavity seal except to re-open the valve leading from the external tank so that pressure could be adjusted; in each case, the ultrasonics were only applied for a few seconds and several minutes elapsed between tests.

In the tests described below, no intentionally-added dissolved or bubbled gas was added to the sample liquid. In previous tests, intentionally placed gas bubbles were quickly pushed out of the acoustic field at the time the ultrasonic transducer was activated, and did not appear to otherwise interact with the ultrasonic wave.

Ambient Pressure:

The ambient pressure case for ultrasonic excitation in the test cavity was performed on multiple occasions. When an evacuated cavity was used to draw in the liquid (as opposed to hand-pouring), a back pressure of a few psi was used to force the test liquid into the cavity; thus, the absolute pressure in the cavity might be as high as approximately 20psi. In the "hand-poured" cases, the absolute pressure

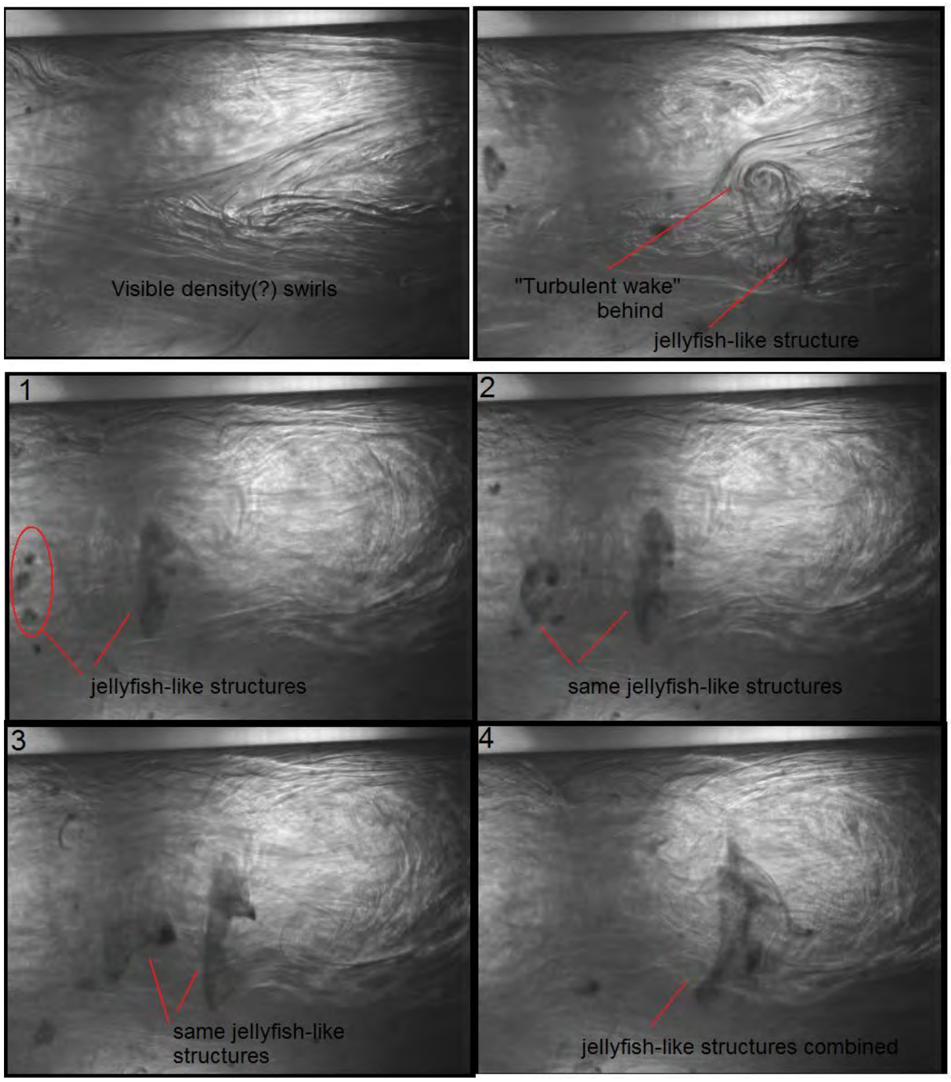
would have been ~13.2 psi due to the altitude of our test site. In the ambient pressure cases, we ran various power levels, ranging from ~1 Watt up to approximately 200 Watts net (forward minus reverse power). The most recent tests included use of the ultrasonically-conductive gel and a 0.001" metal membrane (to separate the test liquid from the gel) attached with a modified double-knife-edge system. During some tests at these low pressure levels, limited or no cavitation bubbles were observed even at high power levels. We are unsure if this was due to some variable in the test liquid, or another unmeasured variable in the system. However, when cavitation was observed, it would typically first be observable near approximately 75 Watts net. As power increased above that level, the number of cavitation bubbles would typically increase dramatically. Most commonly, the cavitation was characterized by two classes of bubbles. There were long-lived clouds of bubbles forming a ring shape that pulsated in size as it moved downstream (away from the transducer) -- we termed these formations "jellyfish" due to the observed motion. There were also much shorter-lived clouds arranged in a more spherical group that often (but not exclusively) burst into appearance near the jellyfish formations, would quickly dart in any direction, and then disappear. Typically, the jellyfish formations might expand and contract from 0.5-2 mm in diameter up to 3-5 mm diameter. At higher power levels, the apparent jellyfish formations would often expand to nearly the full diameter of the test cavity and dissipate. At lower power levels, the jellyfish might traverse the full field-of-view available to the camera. A series of screenshots recorded via high-speed camera on 2010-12-13 are shown below; net power was 145 W:



<u>50 psi:</u>

Using a back pressure of 50 psi to force the viscous test liquid into the test cavity, a total pressure in the cavity of over 60 psi was achieved. The only ultrasonic power level utilized at this pressure was 180 Watts. A different optics set was used during these higher pressure tests, achieving a slightly higher zoom level on the system (25-30 micrometers/pixel). The first detail noticed at higher pressure was that the entire cavity was filled with swirls (possibly density gradients) that seemed to move with the bulk circulation of the liquid). In our own testing, especially during high power tests during which no cavitation was observed, a single, slow-moving swirl line would often be observed. However, in this case, the swirl lines filled the cavity and a clear flow pattern, including interactions/disturbance by bubble clouds, could be observed. In discussions with other scientists who have worked with this liquid, similar swirls have been observed before in other tests, possibly indicating some dissociation or separation of the molecular components of the test liquid.

Additional observations during the 50 psi case included bubble clouds somewhat similar to the "popcorn" and "jellyfish" formations observed at ambient-pressure conditions. The clouds/formations were perhaps a bit larger in all dimensions than those observed at lower pressures. Additionally, some of the distinction between the "jellyfish" and "popcorn" was lost -- popcorn formations were generally longer-lived, often traversing a significant portion of the field of view before disintegrating. Jellyfish type formations were less distinct rings, and typically disintegrated within ~1 cm of travel. Additionally, the popcorn-like bubbles were generally swirling in/around the jellyfish formations. The turbulent wake of some of the jellyfish-like formations could also be visualized via the motion of the apparent density swirls in the flow. Some of these phenomena, recorded via high-speed camera with 180 Watts net of ultrasonic power, are illustrated below (recorded 2011-02-23):



<u>200 psi:</u>

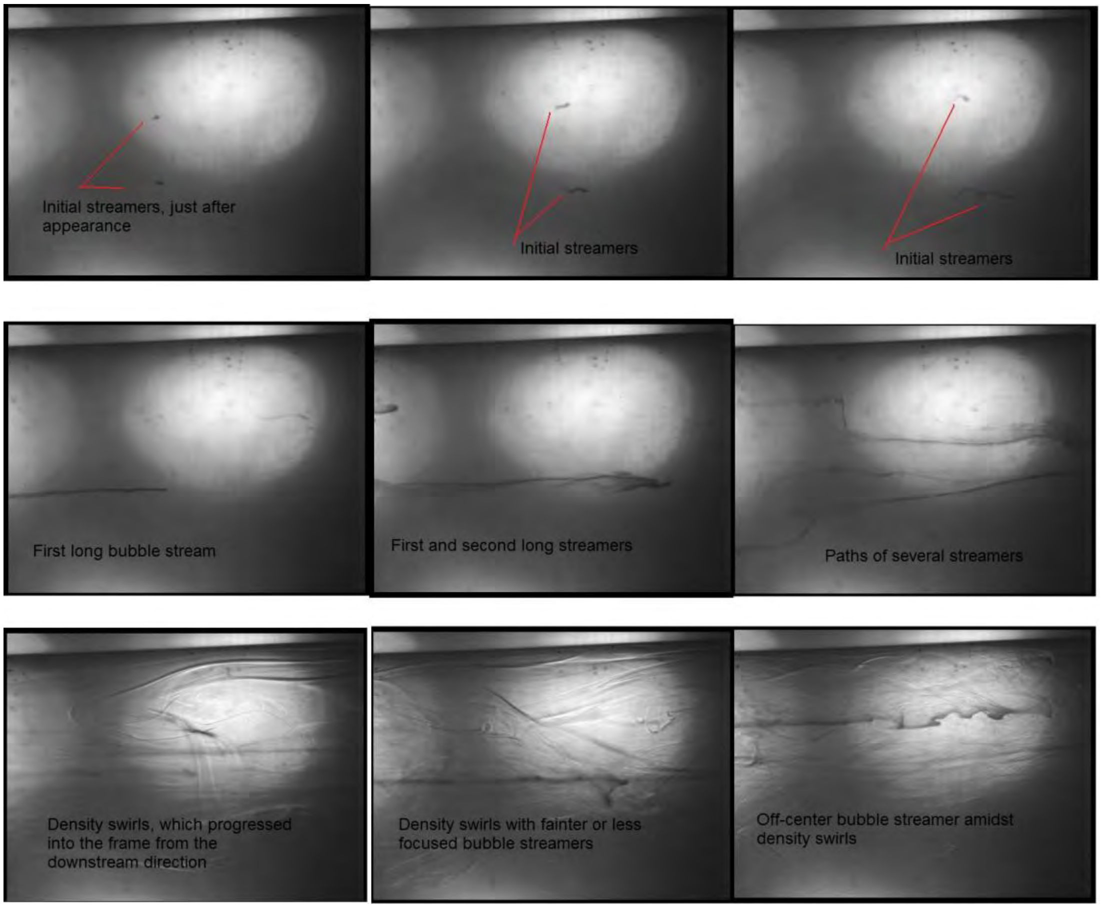
At 200 psi of back pressure used to push the liquid into the cavity (~213 psi absolute), distinctly different bubble behavior was observed. Power level here was 141 Watts net (though the same function

generator voltage amplitude was supplied to the amplifier as in the 50 psi case). Rather than forming defined clumps, bubble motion was primarily defined by long, thin streams or tight bubble clusters with long tails. In full motion video, some "popcorn"-like bubble dynamics were observed, but these clouds were very short lived and smaller in diameter than the streamers.

The initial pair of streamers that appeared just after turning on the ultrasonic power seemed to appear mid-channel and travel downstream (away from the transducer) before dissipating somewhat after ~1 cm of motion. At approximately the same time as that dissipation, however, a streamer that began upstream of the field-of-view came into the frame, and its motion (and visual tail) extended across the entire field of view. This began a cascade of additional streamers coming from off-camera and crossing the visual field, with some slight pausing and expansion (jellyfish-like) motion detectable in the "heads" or concentrated regions of each stream. The diameters of the streams, and the slightly larger/darker concentrated regions of bubbles that traversed along these continuous paths, was in the fraction-of-a-millimeter range.

Some time after the onset of the apparent cavitation streams, a field of apparent density swirls like those observed at 50 psi came into view. Though not as dense/active as those observed at 50 psi, these swirls seemed to indicate a bulk fluid circulation pattern, and had some interaction with the bubble streamers.

Initially, the bubble streams that appeared upstream of the camera frame seemed to enter the frame from a wide range of vertical positions, but focus themselves toward the center as they moved downstream. Later, however, streams were observed to enter and leave the frame far from the vertical center. Screen-captured images from the high-speed video illustrating some of these phenomena are shown below (recorded 2011-02-23):



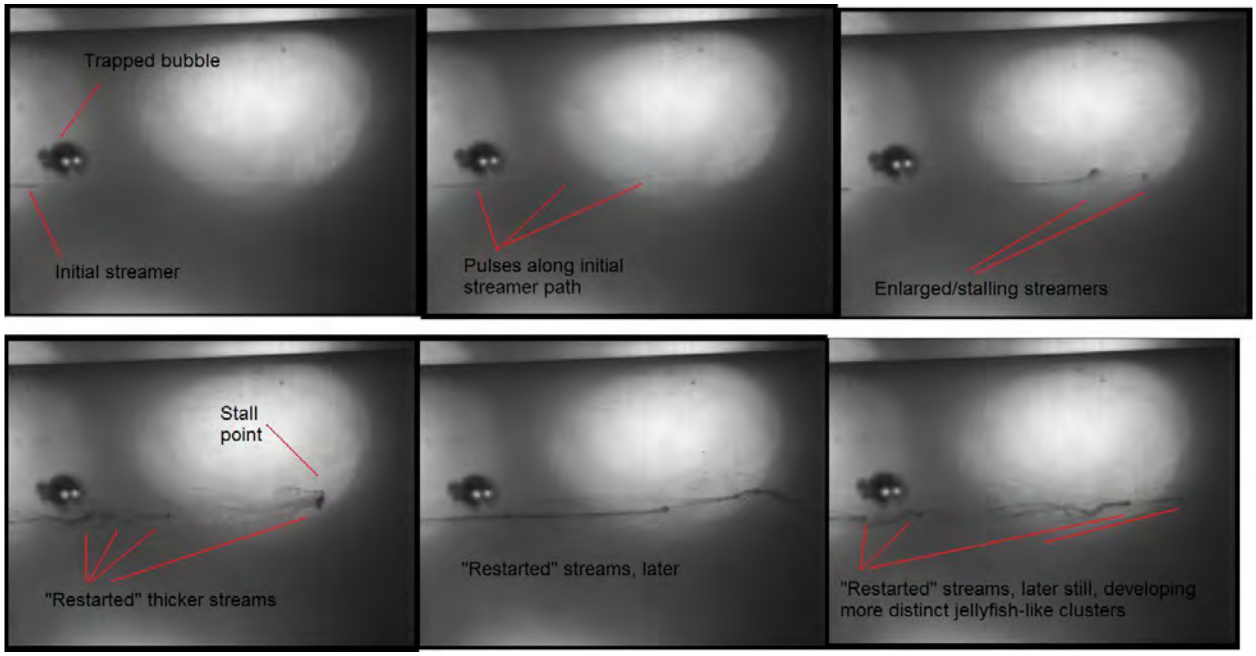
<u>450 psi:</u>

At 450 psi, behavior was somewhat similar to the 200 psi case. Initially, a narrow stream of bubbles (perhaps half the thickness of the 200 psi streams) began to progress from upstream of the frame across the field of view. This streamer had a similar motion, with some small pulsating clumps, as observed previously. The streamer did appear to hit a "stall" point near the downstream side of the field of view.

For some time, all visible bubble motion disappeared, but restarted with much larger/thicker streams with larger clusters or heads with somewhat more apparent jellyfish behavior. The largest clumps were on the order of 1/2 mm in size. The initial motion of the restarted streams did seem to hit a "stall" point on the downstream end of the frame, but as the bubble motion continued, this point seemed to evolve into a curve in the bubble path. More distinct clumps of jellyfish-like clusters seemed to develop a pulsating motion as time went on.

The pattern of bubble action being apparently continuous, then stopping for a time, then restarting in a similar streamer/small jellyfish pattern, continued throughout the recorded video.

A depiction of some of these phenomena is shown in the images below (recorded 2011-02-23):



<u>Notes on bubble motion:</u>

At all pressure levels, the velocity of the bubbles was similar; jellyfish-type formations had bulk velocities of roughly 1 m/s and popcorn formations had velocities of several m/s. As an example, for the 50 psi case, a sampling of velocity measurements were made. Jellyfish-formation velocities ranged from 0.7-1.3 m/s and popcorn formations ranged in velocity from 3.4-4.1 m/s. It is noted that even at the highest bubble velocity observed, several hundred oscillations of the ultrasonic wave would occur during the time required for the bubble to travel one wavelength. Even for the very different bubble types observed at various pressure levels, the order of the velocity remained within the order of 1 to several m/s.